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Abstract

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Electromagnetically induced transparency of charge pumping in a triple-quantum-dots with Λ -type level structure

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We demonstrate an electromagnetically induced electron transparency (EIET) in electron transport through a coupled triple-quantum-dots system under two radiation fields. The direct evidence of EIET is that an electron can travel from the left dot to the right dot without any effect from the center dot. The EIET (position, height, and symmetry) can be tuned by several controllable parameters of the radiation fields, such as the Rabi frequencies and detuning frequencies. The result offers a resonant transport tuning technique using radiation fields. © 2013 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4803072>]

A quantum system under a time dependent potential can reveal important information related to quantum coherence and quantum interference. A three-level system interacting with two near-resonance fields exhibits some interesting phenomena in quantum optics, chief among them is population trapping (CPT) or electromagnetically induced transparency (EIT). In the past decades, the scattered light spectra,¹ the level populations,² and the dynamics of the system³ were investigated analytically and numerically. It is not until very recently EIT has been experimentally verified in a cavity⁴ and in free space⁵ under a weak probe light field with a single natural or artificial atom. Recent work revealed full influence of the laser field on highly excited reaction pathways.^{6,7} Transparency in atoms irradiated with combined femtosecond laser and extreme ultraviolet fields was controlled by two-pathway quantum interference.⁸ While most experiments used pulsed radiation, continuous-wave (cw) has also been employed to investigate EIT.^{9,10} In this letter, we propose an equivalent EIT in electron transport or electromagnetically induced electron transparency (EIET).

Fast development in the fabrication and control of mesoscopic quantum systems opens an avenue to investigate the optical analogs of a wide variety of quantum effects in condensed matter systems.¹¹ Being easily controllable in size and in the energy levels spacing, artificial atoms, such as quantum dots (QDs) and superconducting circuits,¹² are promising candidates for quantum information and computation devices. Based on the convergence between quantum optics and quantum electronics, a feasible transport mechanism in a photon driving coupled quantum dots system was proposed.¹³ The population inversion has been observed for electron tunneling through a three-level system in an asymmetric double QD irradiated by an external field.¹⁴ Through solving the steady-state solutions of the density matrix equations for a three-level double QD systems, one can obtain the condition for the appearance of a dark state.¹⁵ The two-mode photon-assisted transport can then be examined in a three-level structure.^{16,17} It was suggested recently that scalable quantum computation can be setup using the electrical population transfer in

tunneling-coupled quantum wells¹⁸ and in quantum dot systems¹⁹ where electron transport is coherent.

A common element in the previous work on electron transport through triple QDs system^{19,20} is adiabatic transport. The EIET presented here is not based on adiabatic transport,^{21,22} rather it is based on the interference of two fast oscillating radiation field.

In this work, we demonstrate a quantum coherent tuning mechanism in a coupled triple-QD (TQD) system driven by two external fields. The charge transport can be controlled very sensitively with the parameter of the radiation fields, in both the strong and zero-Coulomb blockade regimes. We shall show that both the detuning parameters and the Rabi frequencies can be used to tune the system in and out of EIET state. Tuning coherence/decoherence of a system is a challenge due to the quantum nature of the electron states. The detrimental effect of electron-electron interaction (Coulomb blockade) on EIET is studied through the calculation of shot noise and the Fano factors.

Our model system is a coupled TQD system shown in Fig. 1, which is a Λ -type three-level structure. The system connects two electronic reservoirs in the left and right.²³ The coupling between the QD3 and QD1(2) is modulated by a radiation field. The Hamiltonian of the TQD is given as

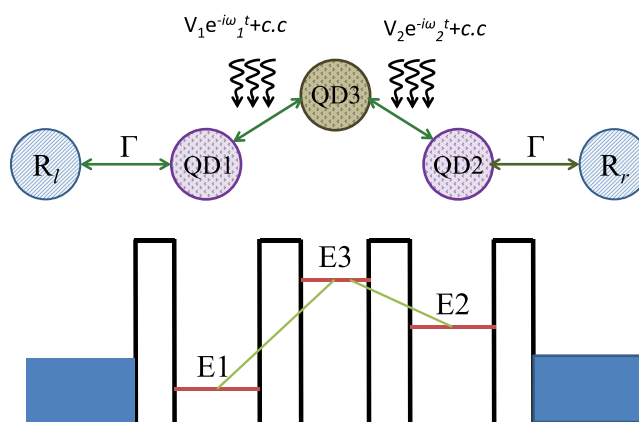


FIG. 1. Schematic diagram of a coupled TQD system in which three ground states form a Λ -type level structure. Two external fields assist the hopping between adjacent levels and the chemical potentials in two electrodes are the same.

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$$H = H_R + H_D + H_T + H_V, \quad (1)$$

where $H_R = \sum_{\mathbf{k}, \alpha=l,r} E_{\mathbf{k}\alpha} c_{\mathbf{k}\alpha}^\dagger c_{\mathbf{k}\alpha}$ describes the electrons in the left (l) and right (r) reservoirs and $c_{\mathbf{k}\alpha}$ ($c_{\mathbf{k}\alpha}^\dagger$) is the annihilation (creation) operator of an electron with wave vector \mathbf{k} in the reservoir α ($= l, r$). The reservoirs are regarded big enough so that they are always in equilibrium in the Fermi energies E_F^α with a continuum distribution of wave vectors \mathbf{k} . $H_D = \sum_i E_i d_i^\dagger d_i$ is the Hamiltonian of the three QDs, d_i (d_i^\dagger), $i = 1, 2, 3$, are the annihilation (creation) operators of an electron in the i th dot. Here, E_i is the energy level of the i th QD. The electronic tunneling between the reservoirs and the connected dots is described by, $H_T = \sum_{\mathbf{k}} (t_{kl} d_1^\dagger c_{\mathbf{k}l} + t_{kr} c_{\mathbf{k}r}^\dagger d_2) + h.c.$. The last term in Eq. (1) describes the radiation-assisted electronic transition, $H_V = V_1 e^{-i\omega_1 t} d_3^\dagger d_1 + V_2 e^{-i\omega_2 t} d_3^\dagger d_2 + h.c.$, where the coupling coefficients V_1 and V_2 are regarded as the Rabi frequencies which relate to the field strength and the electron dipole momentum.¹³ ω_1 and ω_2 are the frequencies of two external fields. In order to see the effect of radiation clearly, we have ignored the effect of direct hopping between the QDs. The time-independent direct hopping will change the total tunneling uniformly under all detuning and Rabi-frequencies. However, the detuning dependence revealed in this work is independent of the direct hopping term. Furthermore in the present system, each QD can only be occupied by 1 or 0 electron. Therefore, there is no dual occupation in any dot. In this case, the spin-degeneracy is not resolved and spin polarization is irrelevant.

In the strong inter-dots Coulomb blockade regime, we assume that only one electron is allowed in the TQD system. We also assume that all relaxation times in the system are much longer than the pulse duration. Using the notation $|n_l, n_c, n_r\rangle$ for a state with n_l, n_c, n_r electrons in the left, center, right QDs, the four base vectors of the Hilbert space are $|a\rangle = |000\rangle$, $|b\rangle = |100\rangle$, $|c\rangle = |010\rangle$, and $|d\rangle = |001\rangle$. The wavefunction can be written in a form of²⁴

$$|\Psi\rangle = \left(b_0 + \sum_{i,\mathbf{k}} b_{i\mathbf{k}} d_i^\dagger c_{\mathbf{k}i} + \sum_{\mathbf{k},\mathbf{k}'} b_{\mathbf{k}'\mathbf{k}} c_{\mathbf{k}'r}^\dagger c_{\mathbf{k}l} + \dots \right) |0\rangle. \quad (2)$$

The coefficients b 's are the time-dependent probability amplitudes for finding the system in the corresponding states. Substituting Eq. (2) into the Schrödinger equation $i\hbar|\dot{\Psi}(t)\rangle = H|\Psi(t)\rangle$ results an infinite set of coupled linear differential equations for $b_{i\mathbf{k}}, b_{\mathbf{k}'\mathbf{k}}, \dots$. The time-evolution of the probability amplitudes can then be obtained with the initial conditions $b_0(0) = 1$ and $b_{i\mathbf{k}}(0) = b_{\mathbf{k}'\mathbf{k}}(0) = \dots = 0$. The electronic dynamics is described by the Markovian rate equations²⁴ for the density matrices $\sigma = \sigma_{XX'}|X\rangle\langle X'|$, where X (a, b, c, d) refers to the i th ($i = 1, 2, 3$) quantum dot. For $X = a$, we have

$$\sigma_{aa} = |b_0(t)|^2 + \sum_{\mathbf{k},\mathbf{k}'} |b_{\mathbf{k}'\mathbf{k}}(t)|^2 + \sum_{\mathbf{k} < \mathbf{k}_1, \mathbf{k}' < \mathbf{k}_1'} |b_{\mathbf{k}'\mathbf{k}\mathbf{k}_1}(t)|^2 + \dots, \quad (3)$$

i.e., $\sigma_{aa} = \sum_{N=0} \sigma_{aa}^{(N)}$, and for $X = b, c$, or d , we have

$$\sigma_{XX'} = \sum_{\mathbf{k}} b_{X\mathbf{k}}(t) b_{X'\mathbf{k}}^*(t) + \sum_{\mathbf{k} < \mathbf{k}_1, \mathbf{k}'} b_{X\mathbf{k}\mathbf{k}_1}(t) b_{X'\mathbf{k}\mathbf{k}_1}^*(t) + \dots, \quad (4)$$

i.e., $\sigma_{XX'} = \sum_{N=0} \sigma_{XX'}^{(N)}$. The diagonal elements describe the probabilities of the electron in a state $|a\rangle$ or $|X\rangle$ (σ_{XX} , $X = b, c$, or d). The off-diagonal elements of density matrices, $\sigma_{XX'}$, describe the superposition among the three QDs. The index N denotes the number of electrons arriving at the right reservoir. The rate equations for the density matrices are given as

$$\dot{\sigma}_{XX} = i \sum_{X'} V_{X,X'} (\tilde{\sigma}_{XX'} - \tilde{\sigma}_{X'X}) - \sum_{X'} (\sigma_{XX} \Gamma_{X,X'} - \sigma_{X'X'} \Gamma_{X',X}) \quad (5)$$

and

$$\begin{aligned} \dot{\tilde{\sigma}}_{XX'} &= i(\Delta_{X'X} - \omega_{XX'}) \tilde{\sigma}_{XX'} \\ &+ i \sum_{X''} (\tilde{\sigma}_{XX''} V_{X'',X'} - \tilde{\sigma}_{X''X'} V_{X,X''}) \\ &- \frac{1}{2} \tilde{\sigma}_{XX'} \sum_{X''} (\Gamma_{X,X''} + \Gamma_{X',X''}) \\ &+ \sum_{X'', X''' \neq X, X'} \tilde{\sigma}_{X''X'''} \Gamma_{X''X''', XX'}, \end{aligned} \quad (6)$$

where $\tilde{\sigma}_{XX'} = \sigma_{XX'} [\exp(i\omega_{XX'} t)]$ is the Fourier transformed off-diagonal matrix elements, $\Delta_{X'X} = (E_{X'} - E_X)/\hbar$ is the energy difference of states $|X\rangle$ and $|X'\rangle$, and $V_{X,X'}$ is the amplitude of one electron hopping that results in the transition between these two states. The width $\Gamma_{X,X'} = 2\pi\rho|t_{X,X'}|^2$ (with density of states ρ) is the probability per unit time for the system to make a transition from the state $|X\rangle$ to the state $|X'\rangle$ in the system due to the tunneling to (from) the reservoirs.

The case of the absence of Coulomb blockade can be analyzed in a similar way. Because more than one electron can occupy the TQD system, the Hilbert space is enlarged in which the four additional base vectors, $|e\rangle = |110\rangle$, $|f\rangle = |101\rangle$, $|g\rangle = |011\rangle$, and $|h\rangle = |111\rangle$, are included.

By using the Laplace transformation $\tilde{b}(\epsilon) = \int_0^\infty b(t) e^{i\epsilon t} dt$, the probabilities $\sigma^{(n)}(t)$ can be obtained via amplitudes $\tilde{b}_{\mathbf{k}'\dots\mathbf{k}\dots}(\epsilon)$ from an infinite set of algebraic equations

$$\sigma^{(N)}(t) = \sum_{\mathbf{k}\dots\mathbf{k}'} \int \frac{d\epsilon d\epsilon'}{(2\pi)^2} \tilde{b}_{\mathbf{k}'\dots\mathbf{k}\dots}(\epsilon) \tilde{b}_{\mathbf{k}\dots\mathbf{k}'}^*(\epsilon') e^{i(\epsilon' - \epsilon)t} \quad (7)$$

and $\sigma(t) = \sum_N \sigma^{(N)}(t)$. We note that $\tilde{\sigma}_{X'X} = \tilde{\sigma}_{XX'}^*$ ($X \neq X'$) and $\tilde{\sigma}_{XX'} = \sigma_{XX'} e^{i\omega t}$. In the following, we shall assume the tunneling rates between the reservoirs and the dots to be independent of energy and use the wide-band limit²⁴ $\Gamma_\alpha = 2\pi \sum_{\mathbf{k}} |t_{\mathbf{k}\alpha}|^2 \delta(E_{\mathbf{k}\alpha} - E_i)$ with α ($= l, r$) and $i = 1, 2$. If not specified otherwise, we assume $\Gamma_l = \Gamma_r = \Gamma$ and Γ is taken as the energy unit. Taking into account the conjugate equations of the off-diagonal elements and $\sum_X \sigma_{XX}(t) = 1$, the equations describing the time evolution of the system are closed. The current can be obtained by²⁴ $I = e \sum_N N \sum_X \dot{\sigma}_{XX}^{(N)}(t)$, where N denotes the number of electrons tunneling to the collector. The stationary current can be found by taking time-average over T , $\bar{I} = e\Gamma\bar{\sigma}_{dd}$, with $T \rightarrow \infty$.

In Fig. 2, we show the dependence of the stationary current I_S on detunings $\delta_1 = E_3 - E_1 - \omega_1$ and $\delta_2 = E_3 - E_2 - \omega_2$ for different Rabi frequencies V_1 . The result exhibits interplay of two-step sequential transport and single

resonant transport across the three dots. When the energy levels E_3 and E_2 are in resonance $\delta_2 = 0$, the current is symmetric about the detuning δ_1 . For $V_1 \ll V_2$, the electron transport takes two steps. An electron hops from QD1 to QD3 with an excess energy δ_1 . If this excess energy equals to the Rabi frequency V_2 (or hopping bandwidth between QD3 and QD2), i.e., $\delta_1 = \pm V_2$, a resonant transport occurs. This is a two-step sequential resonant transport. This case is shown in Figs. 2(a) and 2(b). On the other hand, if the two hopping bandwidths are exactly matched, $V_1 = V_2$, electrons transfer from QD1 to QD3 has a 100% probability to travel to QD2. In this case, a zero excess energy between QD1 and QD3 results an exact resonant condition for travel from QD1 to QD2. As a result, the current peak occurs at $\delta_1 = 0$. This also give rise to EIET around $\delta_1 = 0$ for the Λ -type coupled TQD. In the transition regime as V_1 increases gradually, the current increases. The increase is most rapid around $\delta_1 = 0$. The Coulomb blockade reduces the current significantly. In the absence of Coulomb blockade, the total current increases by at least a factor of 2, as shown in Fig. 2(b). If the energy levels E_3 and E_2 are off resonance, $\delta_2 \neq 0$, the current peak will move according to the required energy shift, shown in Figs. 2(c) and 2(d). For example, $\delta_2 > 0$ corresponds to that the level E_3 is above the E_3 - E_2 energy match by an amount δ_2 , as a consequence, δ_1 required for current resonance increases. Under fixed V_2 , the number of electrons traveling from QD1 to QD3 is proportional to the Rabi frequency V_1 . As a result, it is observed in Fig. 2(a) that the total current, $\int d\delta_1 j(\delta_1)$, is directly proportional to V_1 . In the zero Coulomb blockade case, the peak

current increases by a factor of 2 and the total current increases by a factor of 5. In other words, the Coulomb blockade in this Λ -type coupled TQD reduces the total current by 80%. The very different roles of two detuning parameters can be seen in Figs. 2(e) and 2(f) where the current vs δ_2 is presented. When δ_1 is fixed, the intermediate energy of the electron in QD3 is fixed. In this case, only one value of δ_2 satisfies the resonance condition. The resonance occurs around $\delta_2 = \delta_1 + \Omega$, where Ω is proportional to the difference of two Rabi frequencies.

The limiting case of $\omega_2 \rightarrow 0$ (i.e., the field between the QD3 and QD2 approaches the dc limit) offers the most convincing evidence of EIET in the present system. We take arbitrarily $E_3 - E_1 = 200\Gamma$, $E_3 - E_2 = 100\Gamma$. The pattern of the stationary current is shown in Fig. 3(a). It is found that two peaks would be observed, obviously, one of the location is near $\delta_1 = 0$, where the resonance occurs between E_1 and E_3 . Another peak locates at around $\delta_1 = 100\Gamma$. It seems that a virtual energy level has been shifted equal to energy level E_2 and a resonant response takes place. If δ_1 is near 100Γ , where the crest happens, the population of E_3 is extremely small compared to E_2 . The electron seems to tunnel directly into the right QD and the energy level E_3 becomes invisible. The energy level E_3 acts as an auxiliary state, originally developed for transferring population between two long-lived energy levels optically connected to it. Correspondingly, the occupation in the QD3 is exponentially suppressed.²⁵ In the inset of Fig. 3(a), we show dependence of peak positions on the two detuning parameters. The position of the second resonance at $\delta_1 \neq 0$ is given by $\delta_1 = \delta_2$. This exact 1 to 1

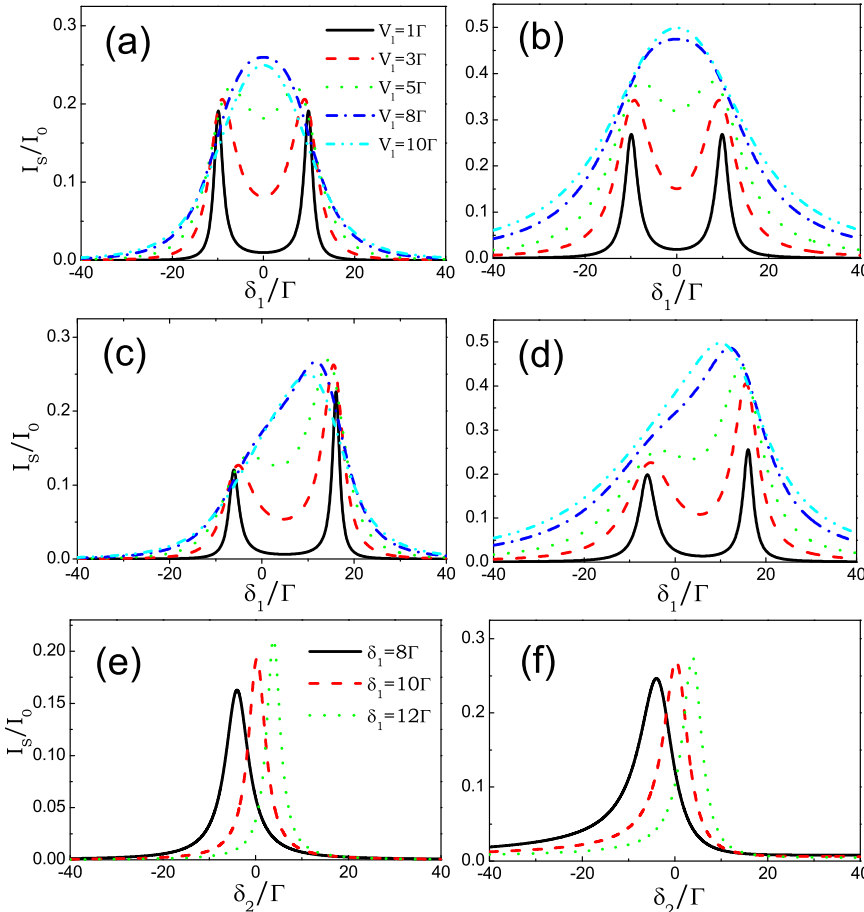


FIG. 2. The left column presents the stationary currents for strong Coulomb blockade situation while the right column exhibits the zero Coulomb blockade regimes. In (a) and (b) the currents vary against δ_1 for different Rabi frequencies V_1 with $V_2 = 10$ and $\delta_2 = 0$. The parameters for (c) and (d) are the same as those in (a) and (b) except for $\delta_2 = 10\Gamma$; In (e) and (f) the stationary currents vary against detunings are shown. Here, $V_1 = 1$ and $V_2 = 10$. I_s refers to the stationary current in the unit $I_0 (= e\Gamma)$.

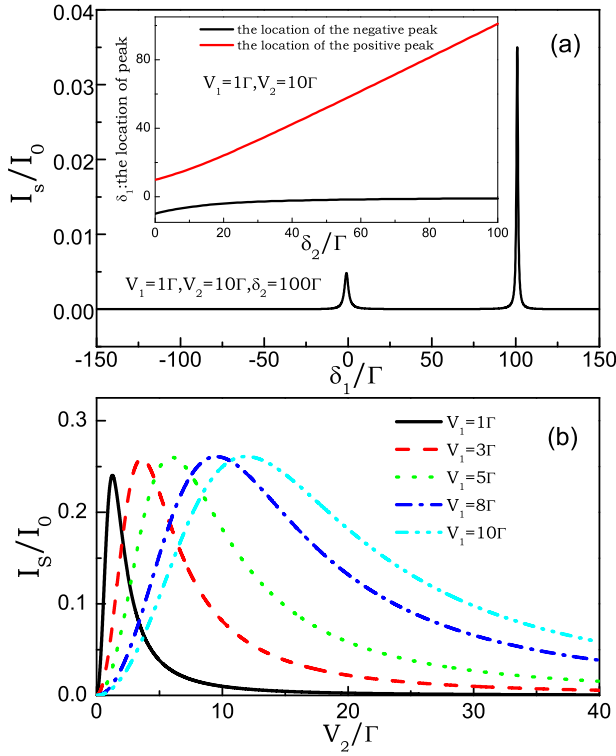


FIG. 3. (a) Stationary current (in a unit $I_0 = e\Gamma$) varies against δ_1 for $\omega_2 \rightarrow 0$ and $\delta_2 = 100$. The inset shows the δ_2 -dependence of the peak location. (b) The variation of stationary current against V_2 for different V_1 , in the strong Coulomb blockade regime for $\delta_1 = \delta_2 = 0$.

correspondence is an evidence of direct coupling of QD1-QD2 and QD3 is irrelevant, or an EIET.

The case of exact energy alignment among three QDs ($\delta_1 = \delta_2 = \delta$) is of interest. Under an exact energy alignment, the stationary current I_S is determined by the amplitudes of two Rabi frequencies. In the strong Coulomb blockade regime, we obtain

$$I_S = \frac{4\Gamma V_1^2 V_2^2}{4(2V_1^4 + V_1^2 V_2^2 + V_2^4) + \Gamma^2(2V_1^2 + \delta^2)}. \quad (8)$$

For $\delta = 0$ (or $E_1 + \omega_1 = E_2 + \omega_2$), the QD1 and QD2 are in resonance and the energy in QD3 only acts to modulate the combined U-shaped tunneling barrier. The current resonance occurs when the effective U-shaped tunneling barrier is

symmetric ($V_1 = V_2$), since a symmetric barrier minimizes the decoherence effect. If $V_1 \neq V_2$, boundary mismatch leads to a reduction of tunneling from QD1 to QD2. This behavior is shown in Fig. 3(b). The current peak height (when $V_1 = V_2 = V$) is independent of the magnitude of Rabi frequency for $V \gg \Gamma$. This is a clear indication of quantum coherence effect as the tunneling rate for the quantum resonant tunneling is independent of the barrier height. A straightforward calculation gives the current peak height $I_C = \Gamma/(2\sqrt{2} + 1)$, indeed independent of V .

The shot noise spectrum, which arises from the discrete nature of the electron charge, is given by,²⁶ $S(\omega) = 2e^2\omega \int_0^\infty dt \sin(\omega t) \sum_N N^2 \dot{P}_N(t)$, where $P_N(t) = \sum_{i=a}^{d(h)} \sigma_{ii}^{(N)}(t)$. From the stationary current and the shot noise spectra, the Fano factor is defined as $F = S(\omega)/(2eI_S)$. Fig. 4 shows the dependence of Fano factor on the detuning in the strong (Fig. 4(a)) and zero (Fig. 4(b)) Coulomb blockade limits and on the Rabi frequency (Fig. 4(c)). The Coulomb blockade enhances the noise and reduces the amplitude of stationary current. The noise is particularly strong when the detuning parameter is set at off-resonance. When the stationary current is off-resonance, the shot noise can be greater than the current, results in a Fano factor being greater than 1. In the absence of electron-electron interaction, the only noise is due to the electron-field interaction which is always smaller than the stationary current. In this case, the Fano factor remains smaller than 1 in the whole regime of Rabi frequencies and detuning parameters. In the absence of Coulomb blockade, the Fano factor is everywhere less than (or equal to) unity, corresponding to the conventional sub-Poissonian statistics of anti-bunched electron transfer.

In conclusion, we have shown that the charge pumping and electron transport through a TQD system with Λ -type level structure can be tuned by two radiation fields of distinct Rabi frequencies and wavelengths. We demonstrated the detrimental role of inter-dots Coulomb blockade in single charge transfer through a quantum structure. The Coulomb blockade not only limits the signal current at the resonance but also significantly increases the shot noise. The field induced double resonance in stationary current is revealed. The coherent transport demonstrated here suggests clearly the vanishing occupation of the middle quantum dot. Its detection has been proposed by using noninvasive ballistic quantum point contacts²⁷ which provides a good test for the observation of the

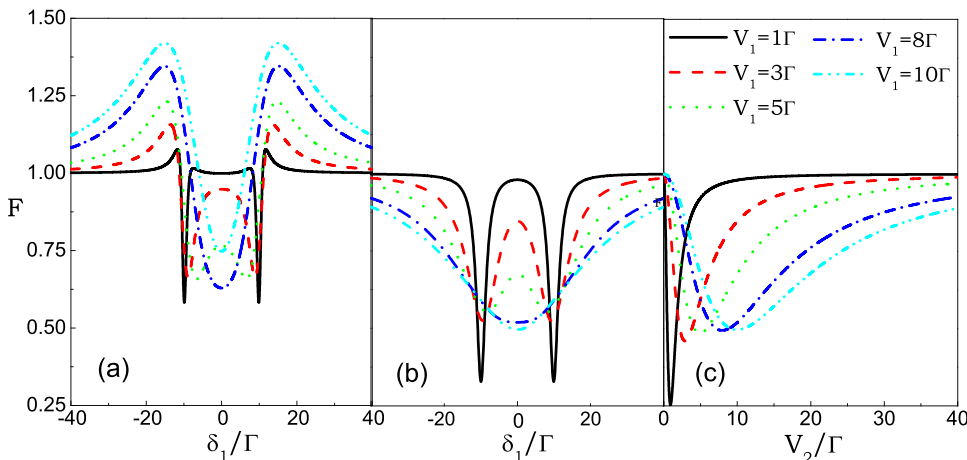


FIG. 4. The Fano factors are presented. The parameters in (a), (b), (c) are taken as in Figs. 2(a)–4(b), and $\omega = 10^{-3}\Gamma$.

dark state precisely. This result offers the possibility of tuning the system in and out of EIET with sharp resolution. For weakly coupled QDs with Γ around a few μeV and a few meV difference of energy levels for adjacent QDs,¹⁴ the reported EIET occurs in the terahertz frequency regime. This unique quantum structure has the potential to be used in application where single color and two color outputs are both required, for example, in detection of terahertz photons. Since the maximum stationary current can be controlled by the two interfering radiation, the proposed EIET can be of potential application in optically switchable current devices.

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